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TITLE – Apollo CM – Analysis of Couch Impact Attenuator Stroke Required for Water Landing

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DATE – March 15, 1967

AUTHOR(S) – J. D. Richey

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ABSTRACT

This study examines the need to protect the astronaut crew of an Apollo CM from impact acceleration during a water landing. Estimates of crew couch impact attenuator stroke and a supporting probability analysis lead to the conclusion that little or no couch attenuator stroke is required to safeguard the astronauts from injury during a water landing. Therefore, it is possible to consider the elimination or reduction of the crew couch impact attenuator stroke provided in the present Apollo CM. Assuming that no significant operational difficulties arise the volume presently reserved for couch movement could, with a minimum of modifications, be utilized to carry additional personnel or equipment.

(NASA-CR-154927) APOLLO CM- ANALYSIS OF COUCH IMPACT ATTENUATOR STROKE REQUIRED FOR WATER LANDING (Bellcomm, Inc.) 27 p

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SUBJECT: Apollo CM - Analysis of Couch Impact Attenuator Stroke Required for Water Landing - Case 330

DATE: March 15, 1967

FROM: J. D. Richey

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TECHNICAL MEMORANDUM

INTRODUCTION

Determination of the feasibility of increasing the capability of the present Apollo CM to carry four astronauts or a varying complement of astronauts and additional equipment, as might be required in ferry or rescue missions, will require detailed examination of equipment designs and operational procedures. Among these are the environmental control system capacity and operation of the CM by crews of one to four astronauts in various physical conditions. However, the key consideration in an evaluation of a four-man CM configuration appears to be the reduction in crew couch landing impact attenuator stroke that would result from placement of an extra crewman in the present couch stroke clearance volume. Preliminary estimates of required couch stroke made in 1964 using scale model test data indicated that for water landings the couch stroke could be significantly reduced or possibly eliminated. During the past two years intermittant effort has been directed toward refinement and validation of the earlier estimates and conclusion. This memorandum records the method and results of this more detailed examination of couch stroke attenuator requirements.

CM CONFIGURATION AND ASTRONAUT ACCELERATION LIMITS

In the Apollo CM, the three astronaut crew rides side by side on a couch assembly that is suspended on impact attenuators which stroke along the X, Y and Z axes of the CM when the acceleration components applied to the couch assembly in these directions exceed predetermined levels. Clearance volume has been provided in the CM to accomodate couch motion resulting from attenuator stroking. Figures 1 and 2 show the proposed method of placing four astronauts in a CM. Two astronauts are located in the center of the CM with the upper astronaut raised so that his knees are in the forward tunnel. The lower astronaut is stacked directly below him. The two outside astronauts are located as in the normal three-man CM configuration. In the three-man configuration there is sufficient clearance between the underside of the couch assembly and the aft bulkhead of the CM to provide 16.5 inches of attenuator stroke. In the four-man configuration of Figures 1 and 2 clearance for attenuator stroke in the -X direction is reduced to 7.5 inches.

The peak acceleration that an astronaut can withstand depends on the design of his suit, restraint harness and couch. An Apollo crewman in his suit, restraint harness and couch as shown in Figure 3, can withstand the normal mission impact limits shown in Figure 4 without injury. In the diagram the small number preceding the slash is the peak acceleration imposed during the landing impact in g per second. The larger number following the slash is the maximum allowable on-set rate in g per second. Figure 5 shows the emergency impact limits. For accelerations beyond these limits it is questionable if the astronaut will survive. An astronaut subjected to a peak acceleration between the limits shown in Figures 4 and 5, will survive but will likely sustain some injury. Scale model drop tests of the Apollo CM indicate that for water impacts the expected accelerations in the Y and Z directions are significantly less than the normal mission limits, while the acceleration in the +X direction (identified by the heavier vectors in Figures 4 and 5) may exceed the normal mission limits. Therefore, it is necessary to analyze impact acceleration in only the +X direction to determine the attenuator stroke required to prevent injury to the astronauts during a water landing.

DROP TEST DATA

The NASA, Langley Research Center has performed a series of drop tests using a one-quarter scale model CM. The model was dropped at a constant vertical velocity at varying water entry angles (angle between the YZ plane of the CM and water surface) and with varying horizontal velocities. Accelerometers were located at the CG of the model CM to measure the accelerations along the X and Z axes. The tests showed that accelerations in the X direction were sensitive to the water entry angle and relatively insensitive to horizontal velocity. The accelerations in the Z direction were not sensitive to either the water entry angle or the horizontal velocity and in all cases were considerably below the normal Apollo mission limits specified in Figure 4. The tests were performed by dropping the model into a towing tank whose water surface was quiescent. Figure 6 shows the model at water impact. Drop test data obtained at a vertical velocity of 23 fps was extrapolated to a vertical velocity of 28 fps and is plotted on Figure 7. It shows that for a given water entry velocity the peak accelerations in the +X direction increase with decreasing water entry angle. Also shown on the graph are the normal mission limit and the emergency mission limit. When the water entry angle is less than fifteen degrees the acceleration exceeds the normal mission limit.

WATER IMPACT PARAMETERS AND ANALYSIS PROCEDURE

Under actual mission conditions the CM will not impact on a quiescent water surface. Instead, the CM will impact on a wave where the water slope and the water vertical particle velocity are described by distributions that are a function of the wind velocity. The wind also has a distribution function which varies with the time of the year and the location of the landing area. Under actual landing conditions (Figure 8), the water entry angle of the CM is a function of the CM suspension angle (27.5° for this study), the wave slope, the random orientation of the toe of the CM with respect to the wave front, the random oscillation angle of the CM ($\pm 4°$ maximum with three parachutes), and the orientation of the oscillation angle with respect to the wave front. The effective vertical entry velocity of the CM is a function of the vertical velocity of the CM and the water particle vertical velocity. For the mid-Pacific landing area the sea conditions are most severe during the month of February. During this month 95% of the time the wind will not exceed 28.5 knots. There is a .99 probability the wave slopes generated by a 28.5 knot wind will not exceed 15°*. Using this value of wind velocity in the following equation** for the variance of water particle vertical velocity, the three sigma limit of particle vertical velocity was computed to be ±9 feet per second.

$$\sigma^2 = \int_{\omega_1}^{\omega_2} \frac{\alpha g^2}{\omega^3} e^{-\beta\left(\frac{\omega_o}{\omega}\right)^4} d\omega$$

where:

$\omega_o = \frac{g}{u}$, where u is wind speed in fps

$g = 32.2$ fps^2,

$\beta = 0.74$

$\omega = \sqrt{g k_o}$, $k_o = \frac{2\Pi}{\lambda}$

λ = wave length in ft

$\alpha = 8.10 \times 10^{-3}$

The lower and upper limits of effective vertical impact velocities of 19 and 37 fps were obtained by combining the ±9 fps with the 28 fps vertical velocity of the CM for the case when all three parachutes are functioning. Accelerations for vertical velocities of 19 and 37 fps were developed by extrapolation and are plotted in Figure 9.

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*CM Water Landing Criteria, Ref. P6-5/L, 114/65-746; Letter from MSC to NAA July 6, 1965.

**Personal Communication from D. E. Cartwright to W. W. Elam of Bellcomm suggested this method of using equation 12 from A Proposed Spectral Form for Fully Developed Wind Seas Based on the the Similarity Theory of S. A. Kitaigorodski, Pierson, Willard J. Jr., and Moskowitz, Lionel, Journal of Geophysical Research, Vol. 29, No. 24, December 15, 1964.

The plot shows, for a given water entry angle, the range of impact accelerations that can be expected and the normal and emergency mission limits.

Analysis of attenuator stroke requirements involves several related investigations. Estimates of the attenuator stroke required to limit the acceleration imposed on the crewmen to a specified value must be developed. Also the probability that the CM will experience acceleration greater than a selected value must be determined. Finally the attenuator stroke estimates and the CM acceleration probabilities must be related. The balance of this memorandum describes a method for estimating the couch impact attenuator stroke and examines the need for attenuator stroke in the Apollo CM by relating estimated attenuator stroke requirements to calculated CM acceleration probabilities. The analysis and computation of the CM impact acceleration probabilities are covered in a companion technical memorandum by Mr. G. R. Andersen.*

IMPACT ATTENUATOR STROKE

In the event that one of the three main parachutes should fail to open the CM vertical velocity would increase from 28 fps to 32 fps.** Adding 9 fps vertical particle velocity to a CM vertical velocity of 32 fps results in an effective water entry velocity of 41 fps. Couch attenuator stroke was estimated for a water entry angle of 10° and effective entry velocities of 32, 37 and 41 fps. These representative severe entry conditions are indicated by points A, B and C respectively in Figure 9.

A plot of acceleration versus time for the 1/4 scale model CM impacting at a 10° water entry angle and with a 32 feet per second vertical velocity is shown in Figure 10. This curve was integrated twice; first to obtain the velocity versus time and then to obtain the acceleration versus time. From these computations a plot of velocity versus displacement was made as shown in Figure 11. Next, Von Karman's impact theory, based on the conservation of momentum, was used to estimate the virtual mass of water attached to the CM as a function of water surface penetration. At a fixed water entry angle, the relationship shown in Figure 12 is valid over a range of entry velocities. Using the virtual mass-water penetration history derived from drop test data, velocity versus displacement was calculated for water entry velocities of 37 and 41 fps at the fixed 10° water entry angle. The results are plotted in Figure 13.

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*"Apollo CM Water Landing Acceleration Probabilities," Technical Memorandum, March 15, 1967, G. R. Andersen.

**Descent velocity data obtained from MSC and subsequently presented at the AS-204 Design Certification Review.

Using the approximation that Δs (incremental distance) $= \bar{V}$ (average velocity) x Δt (incremental time), the velocity - time curves for CM impact velocities of 37 and 41 feet per second were computed. These are plotted in Figure 14 together with the previously calculated velocity-time curve for a 32 fps entry.

Assuming an impact attenuator that will limit acceleration to a constant level, the attenuator stroke can be determined by recognizing that the crew couches and CM will travel together from initial impact until the predetermined acceleration level is reached. At this time the couches will begin to move relative to the CM. The relative motion will continue until both the CM and couches are again traveling at the same velocity. During the period of relative motion a constant acceleration level determined by the attenuator design will be impressed on the crew couches and astronauts.

For an ideal 20 g attenuator this action is illustrated graphically in Figure 14. Three lines, each with a constant slope of 20 g are drawn tangent to the 32, 37 and 41 fps velocity curves. At the indicated points of tangency, relative motion between the CM and couches will begin. At the point where the 20 g lines cross the associated velocity-time curves, relative motion between the couches and CM will cease. Integration of the CM velocity curve from the time when relative motion begins, to the time that relative motion ceases will give the travel of the CM. Integration of the couch velocity curve, which is the 20 g line, from the time relative motion begins until it ceases will give the travel of the couches. The difference between these two distances will be the required attenuator stroke. For a 32 feet per second vertical velocity the stroke of the attenuator was estimated to be .36 inches. For vertical velocities of 37 and 41 fps the stroke was estimated to be 1.0 and 1.37 inches respectively. These estimated strokes for points A, B and C respectively of Figure 9 are shown in Figure 15.

The predicted stroke levels for a 10° entry angle (Points A, B and C) shown in Figure 15 and the peak accelerations developed by extrapolation of the entry velocity as shown in Figure 9 are generally consistant with test data obtained recently from MSC. Four full scale CM drop tests were conducted at the North American Aviation Co. and the results are summarized in Table 1.

TABLE 1

Vehicle Type	Test No.	Vertical Velocity (fps)	Horizontal Velocity (fps)	Water Entry Angle	Roll Angle	Yaw Angle	Max $\ddot{x}$
Block I	100	30	45.1	41°	0.6°	0°	3.7 g
	102	34.2	39.9	15.2°	180°	0°	26 g
Block II	103	31.2	46.9	44.2°	0.2°	0°	10 g
	104	34.3	39.2	13.2°	180°	0°	27 g

The only instance of impact attenuator stroking occurred when the X-X left foot and right foot struts stroked .9 inch and .6 inch respectively during test No. 104. The anthropometric dummies used were 90 percentile, 90 percentile and 10 percentile placed in the left, center and right couches respectively. Also, it should be noted that during these drops there was a momentary deflection in the aft bulkhead of 1-3 inches at the center of the impact area on the Z axis near the lower equipment bay.

ATTENUATOR STROKE AND PROBABILITIES OF ACCELERATION AND WATER ENTRY ANGLE

Figures 16 and 17 are plots of CM peak acceleration probabilities and water entry angle probabilities for the three man parachute case as computed by Mr. G. R. Andersen in the previously mentioned memorandum.* The acceleration probabilities are conditional because in their derivation only water entry angles between 27.5° and 0° were considered and because it was assumed that the water surface was composed only of up-wind and down-wind slopes. Water entry angles greater than the suspension angle of 27.5° are expected to produce impact accelerations that are lower than the impact accelerations produced at water entry angles less than 27.5°. Also, the CM may impact on cross-wind slopes and they are less steep than up-wind and down-wind slopes. Therefore, the unconditional probabilities of the CM experiencing a given impact accelerations or water entry angles are smaller than the conditional probabilities shown in Figure 16 and 17. Selected conditional acceleration and water entry angle probability levels are combined with the water entry angle versus peak acceleration curves on Figure 18. The probability of the CM impacting the ocean surface under conditions that occur to the right of the vertical line at 35 g (through Point A) in Figure 18 is less than .0012. Also, the probability of the CM impacting the ocean surface with a water entry angle less than 10° (through A and B)** is less than .002. While the exact probability of the attenuator stroke exceeding .3 inches (Point A) cannot be inferred from these data, it is certainly less than .002.

Some recent data on the structural limit of the heat shield has been added to Figure 18***. It appears that the probability of exceeding the structural limit of the heat shield during a water landing is small. Also, it should be noted that the heat shield structure will fail at an impact acceleration level that is well below the emergency limit.

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*See Footnote Page 4.

**The probabilities shown on Figure 18 do not apply to Point C which represents a condition for the two parachute case.

***From AS-204 Design Certification Review.

CONCLUSIONS

The low probability that impact protection will be needed for water landings makes it possible to consider eliminating or reducing the crew couch impact attenuator stroke presently provided in the standard Apollo CM configuration. Use of the volume beneath the couches (now reserved for couch stroke in the -X direction) could provide alternate or extended mission capability. The four-man configuration offers the possibility of one astronaut piloting the CM to an operational or rescue site and returning with three additional astronauts. Other combinations of men and equipment payloads can be readily visualized. Clearly, there are design and operational considerations to be resolved before such extended capability can be established as feasible. These include, the capability of one man to fly the CM, the necessity of retaining impact protection for the case of pad or launch aborts that could terminate in land landings, and the deflection of the aft bulkhead during water landing tests. Assuming these problems can be resolved favorably, continued use of water landings with the present CM offers the possibility of extending the Apollo CM capability in a minimum time and with a minimum of modification.

The contributions of Messrs. G. R. Andersen and W. W. Elam to this analysis are gratefully acknowledged.

J. D. Richey

2033-JDR-dfr J. D. Richey

Attachments
Figures 1-18

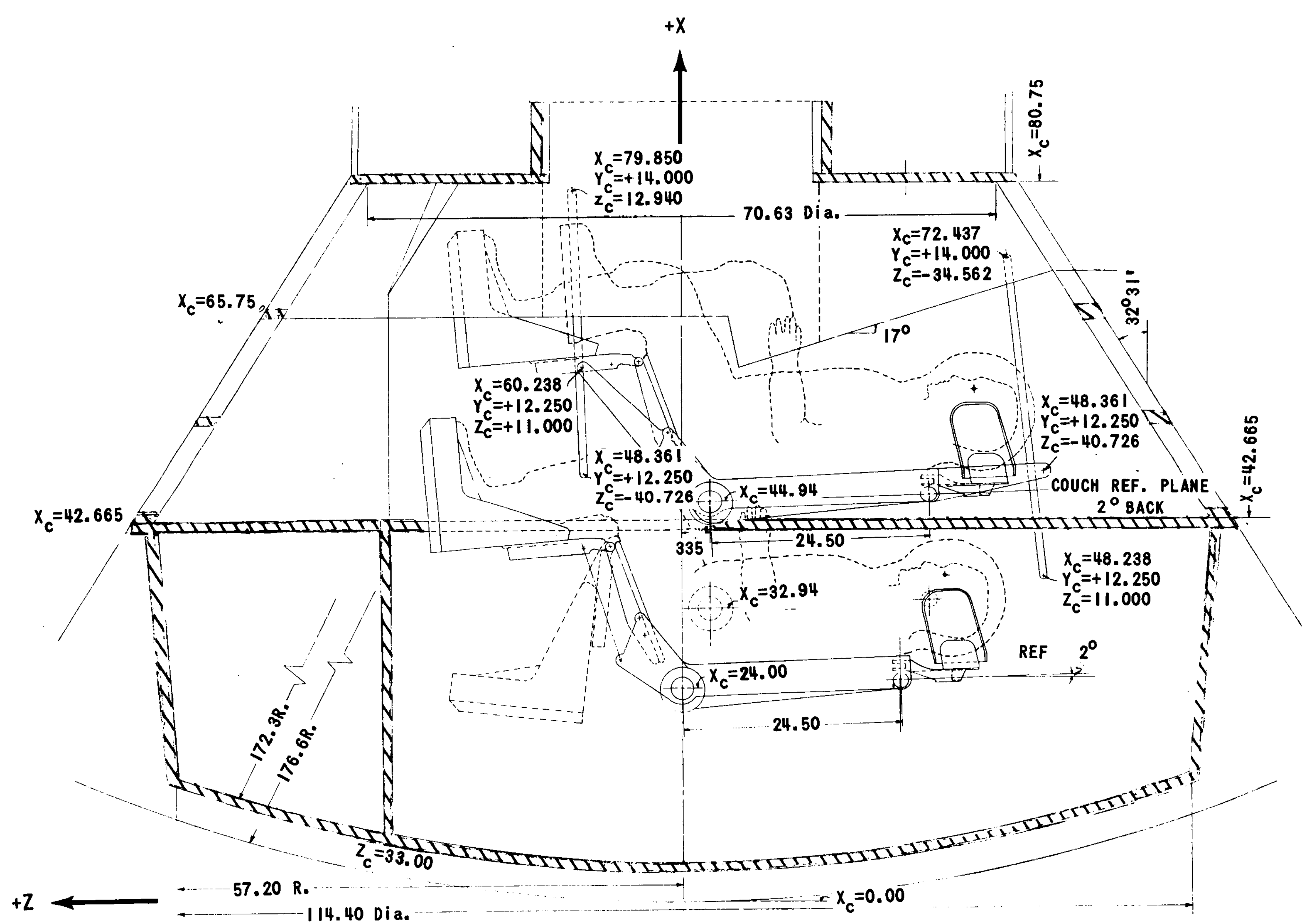


FIGURE I - LAY OUT OF PLACEMENT OF CENTER CREWMEN IN PROPOSED 4 MAN CM

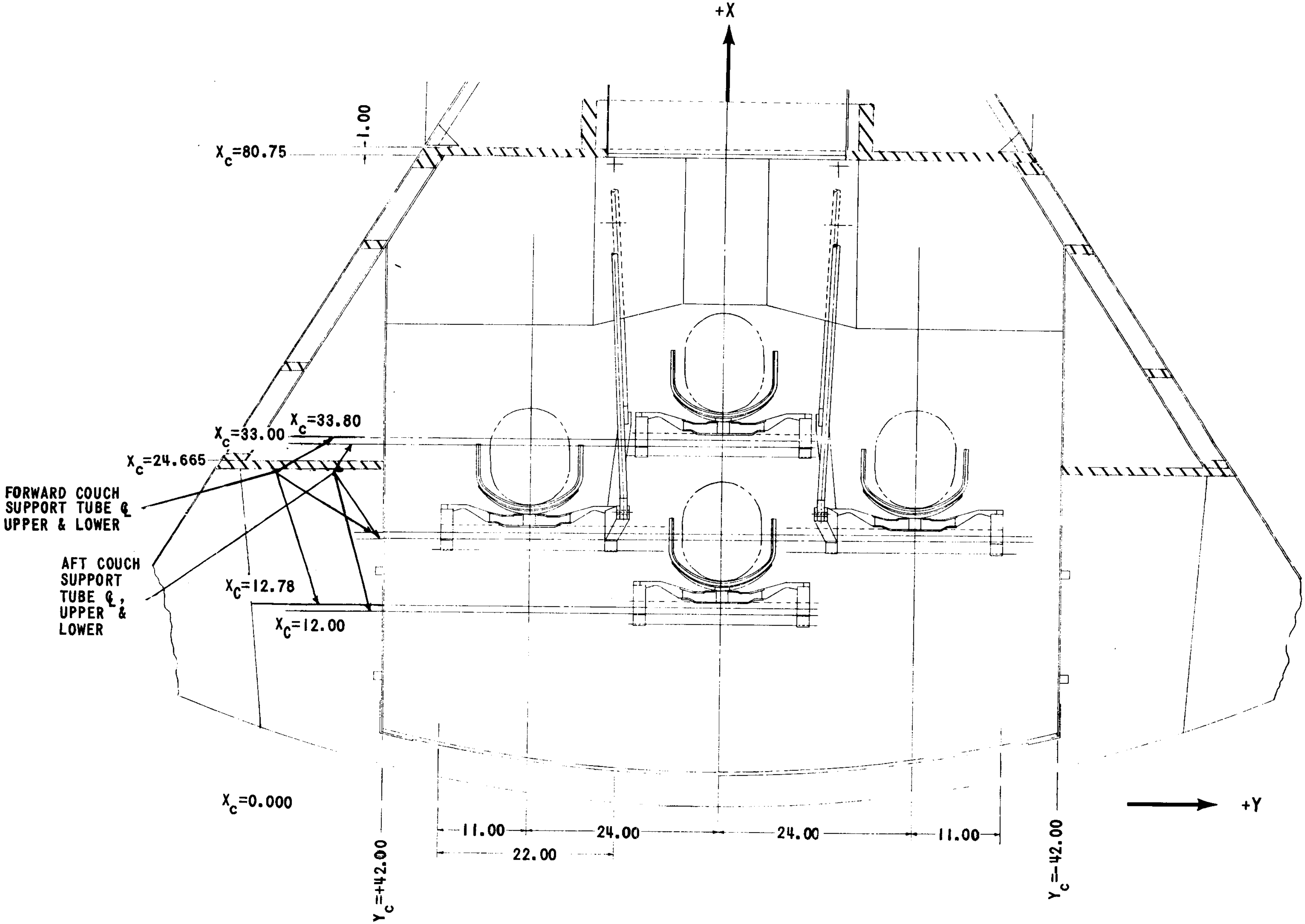


FIGURE 2 - END VIEW OF FIGURE 1

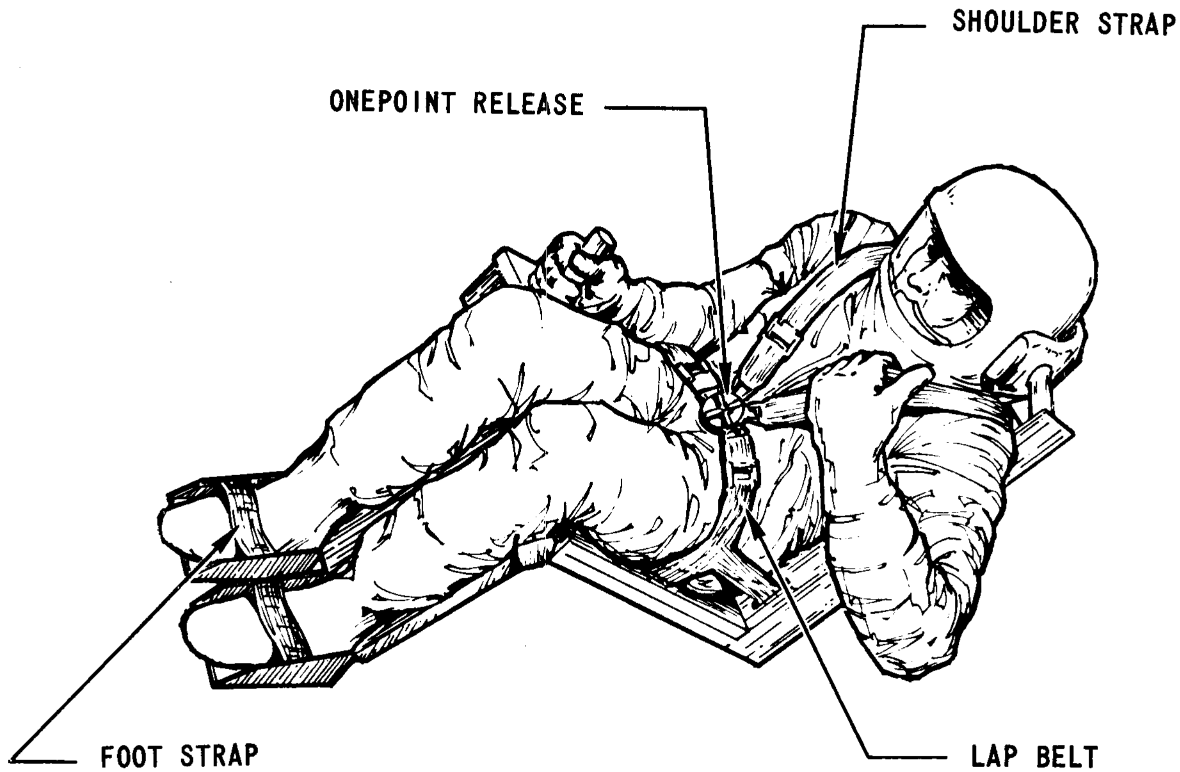
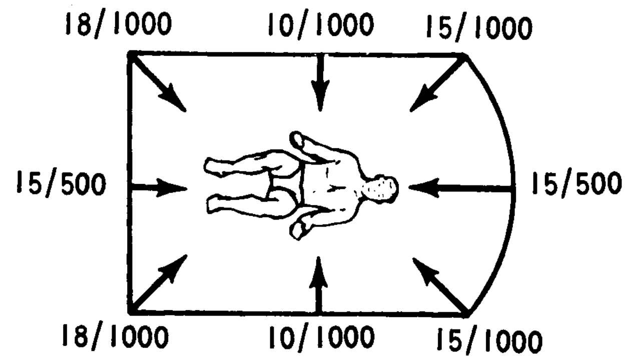


FIGURE 3 - RESTRAINT HARNESS

FROM NASA-S-64-4133

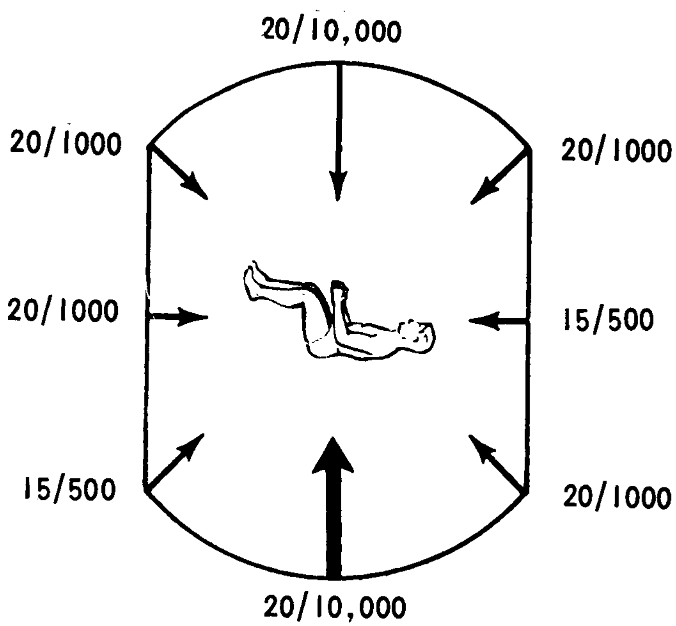
CORONAL PLANE SECTION



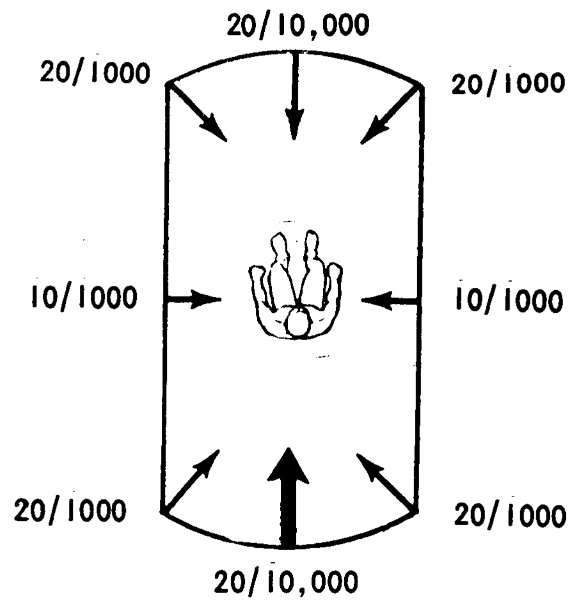
NOTE:

A. RESTRAINT AND SUPPORT MUST BE SIMILAR TO FIGURE 3

B. ARROWS INDICATE DIRECTION, MAGNITUDE, AND ON-SET RATE OF MAXIMUM ACCEPTABLE APPLIED ACCELERATION FORCE FOR NORMAL MISSION LIMITS



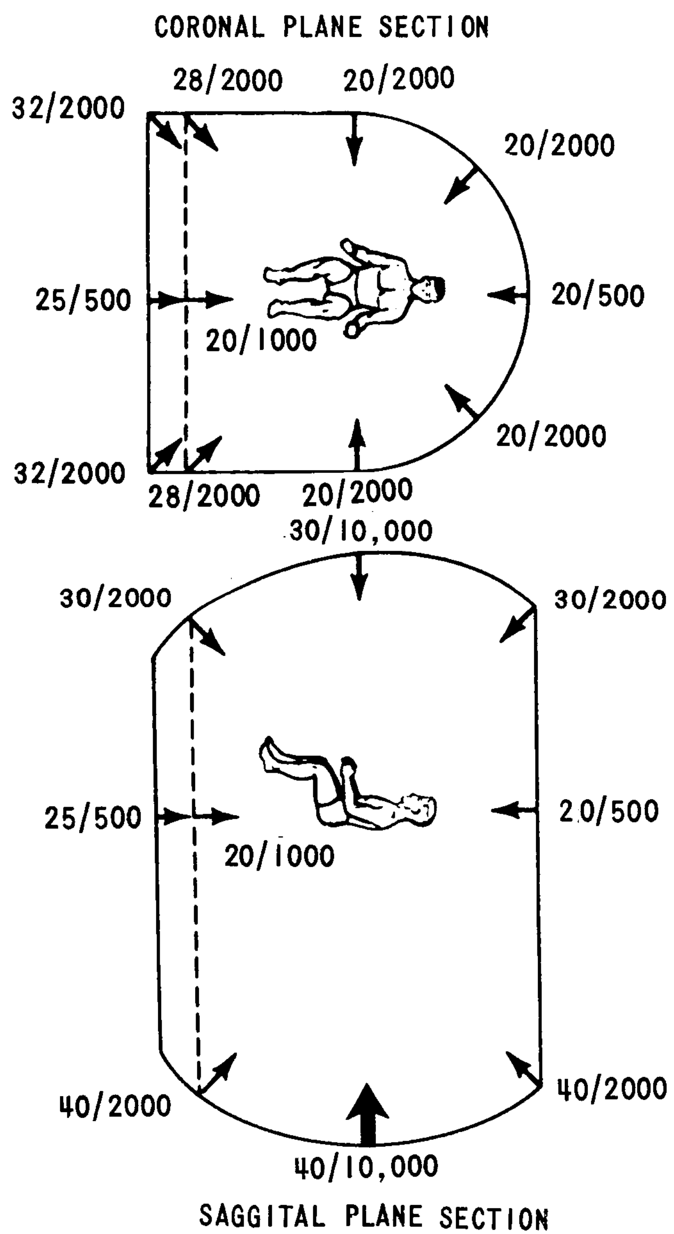
SAGGITAL PLANE SECTION



TRANSVERSE PLANE SECTION

FIGURE 4 - APOLLO NORMAL MISSION IMPACT '.IMITS

FROM NASA-S-65-1711



NOTE:

A. SUPPORT AND RESTRAINT MUST BE SIMILAR TO FIGURE 3

B. ARROWS INDICATE DIRECTION, MAGNITUDE, AND ON-SET RATE OF MAXIMUM ACCEPTABLE APPLIED ACCELERATION FORCE FOR THE EMERGENCY MISSION LIMITS

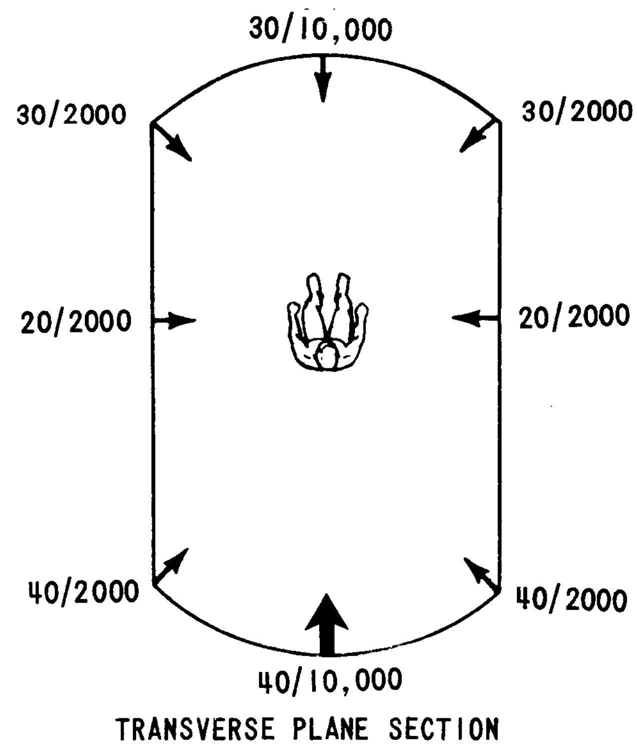
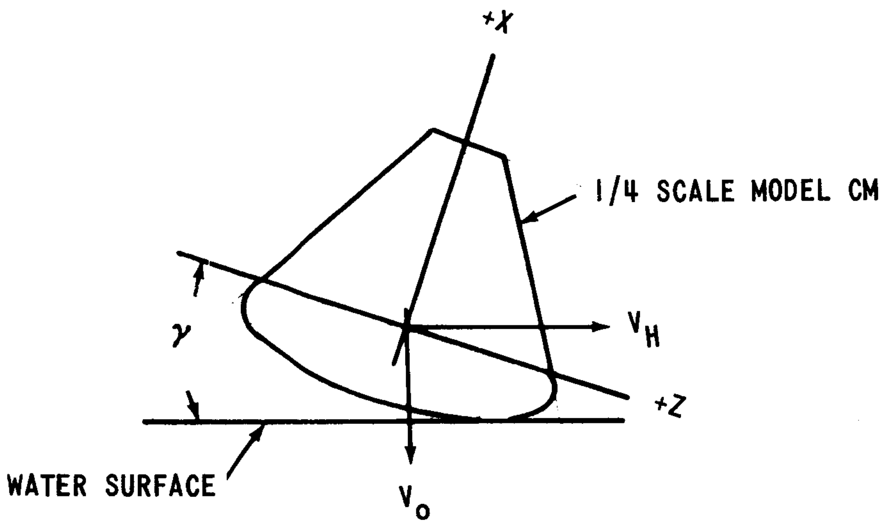


FIGURE 5 - APOLLO EMERGENCY IMPACT LIMITS

FROM NASA-S-65-1710



V_O = VERTICAL VELOCITY
V_H = HORIZONTAL VELOCITY
γ = WATER ENTRY ANGLE

FIGURE 6 - DROP TESTS

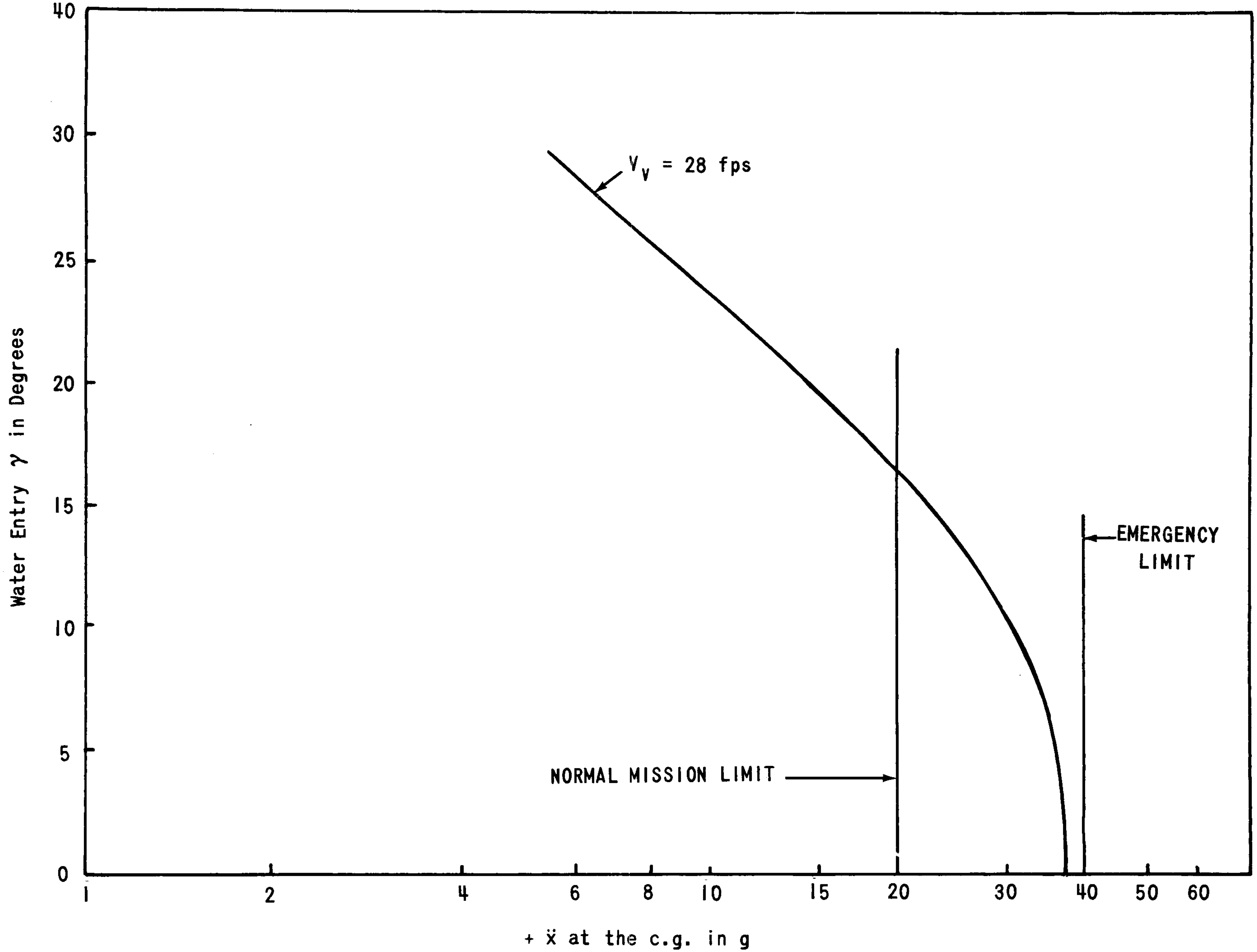
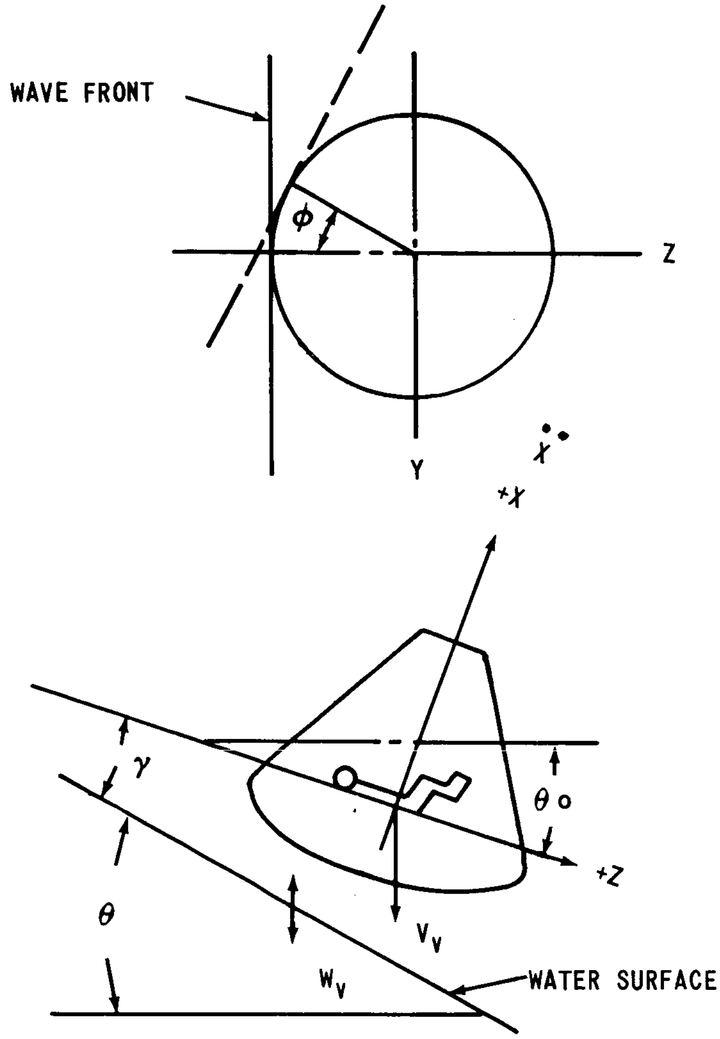


FIGURE 7 - CM WATER LANDING PEAK IMPACT ACCELERATIONS VS. WATER ENTRY ANGLE FOR VERTICAL DROP VELOCITY OF 28 FPS. (EXTRAPOLATED FROM 1/4 SCALE MODEL TEST DATA WITH V_V = 23 FPS)



γ = WATER ENTRY ANGLE - A FUNCTION OF SUSPENSION ANGLE θ_o AND ORIENTATION ANGLE ϕ , OSCILLATION ANGLE (β) AND ITS ORIENTATION ANGLE (α), WAVE SLOPE θ.

(V_R) = VERTICAL ENTRY VELOCITY - A FUNCTION OF VERTICAL VELOCITY OF CM V_V , WAVE PARTICLE VERTICAL VELOCITY W_V.

FIGURE 8 - WAVE AND CM AT IMPACT

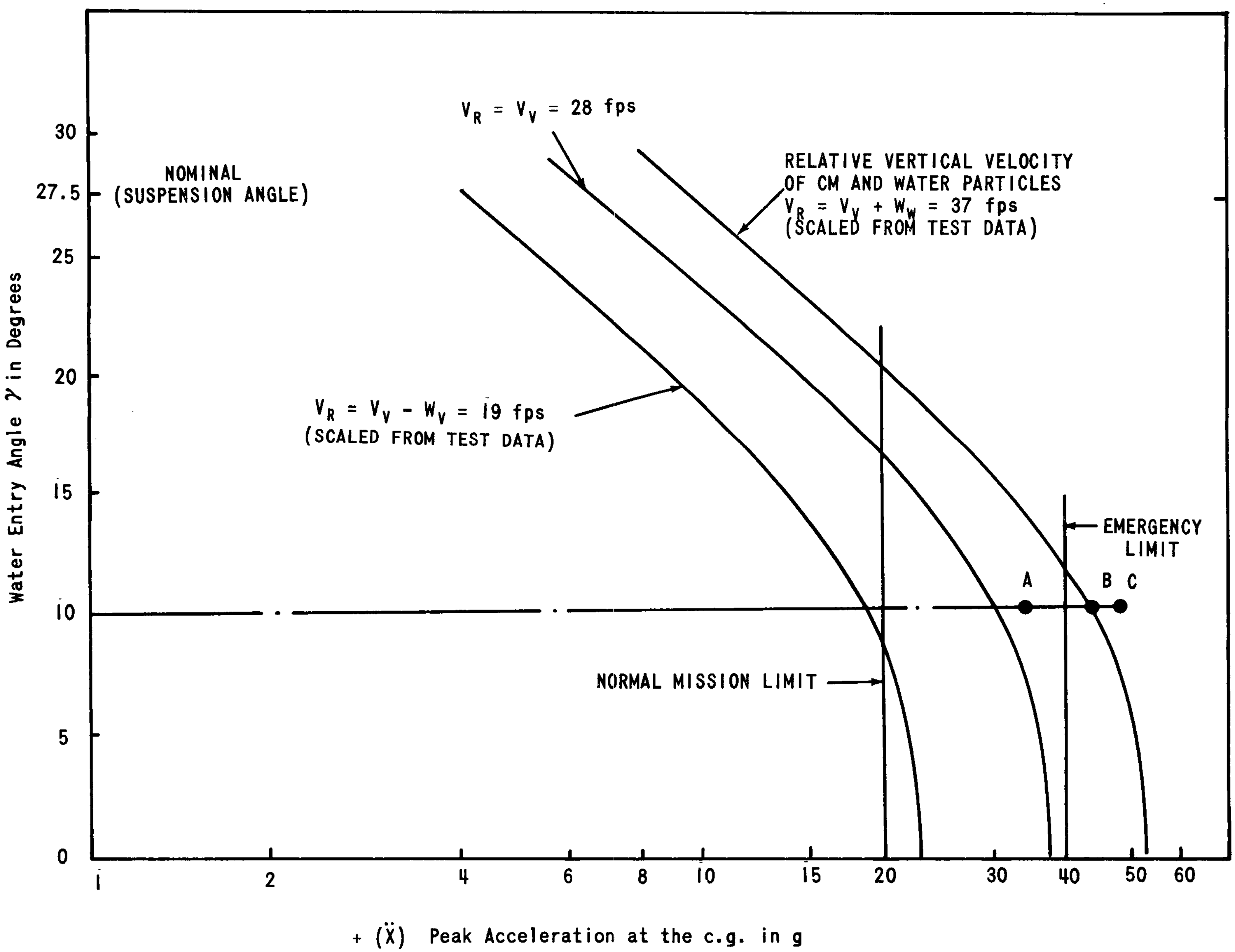


FIGURE 9 - CM LANDING PEAK IMPACT ACCELERATIONS VS. WATER ENTRY ANGLES (WIND VELOCITY = 28.5 KNOTS)

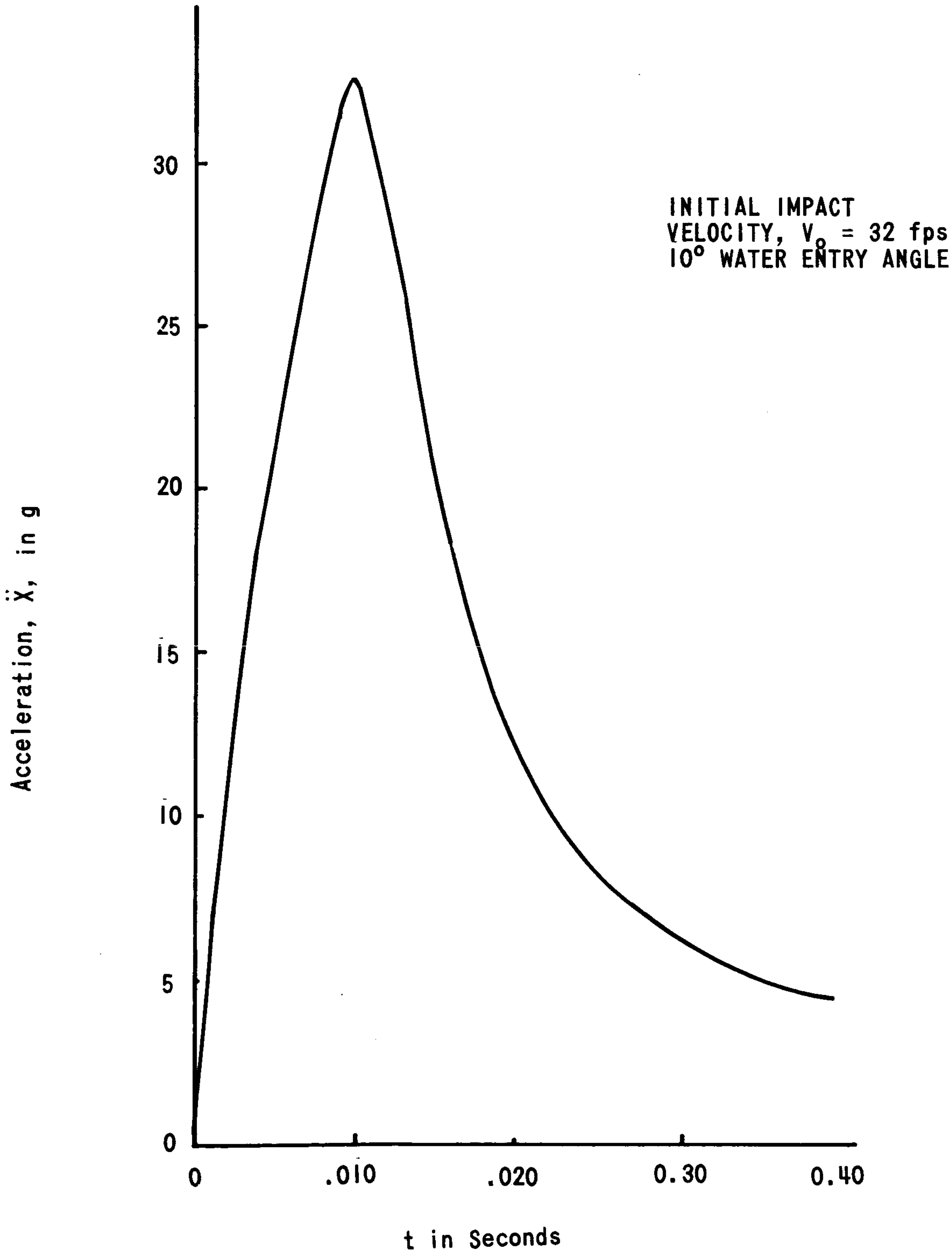


FIGURE 10 - WATER IMPACT DATA BASED ON 1/4 SCALE MODEL CM TEST

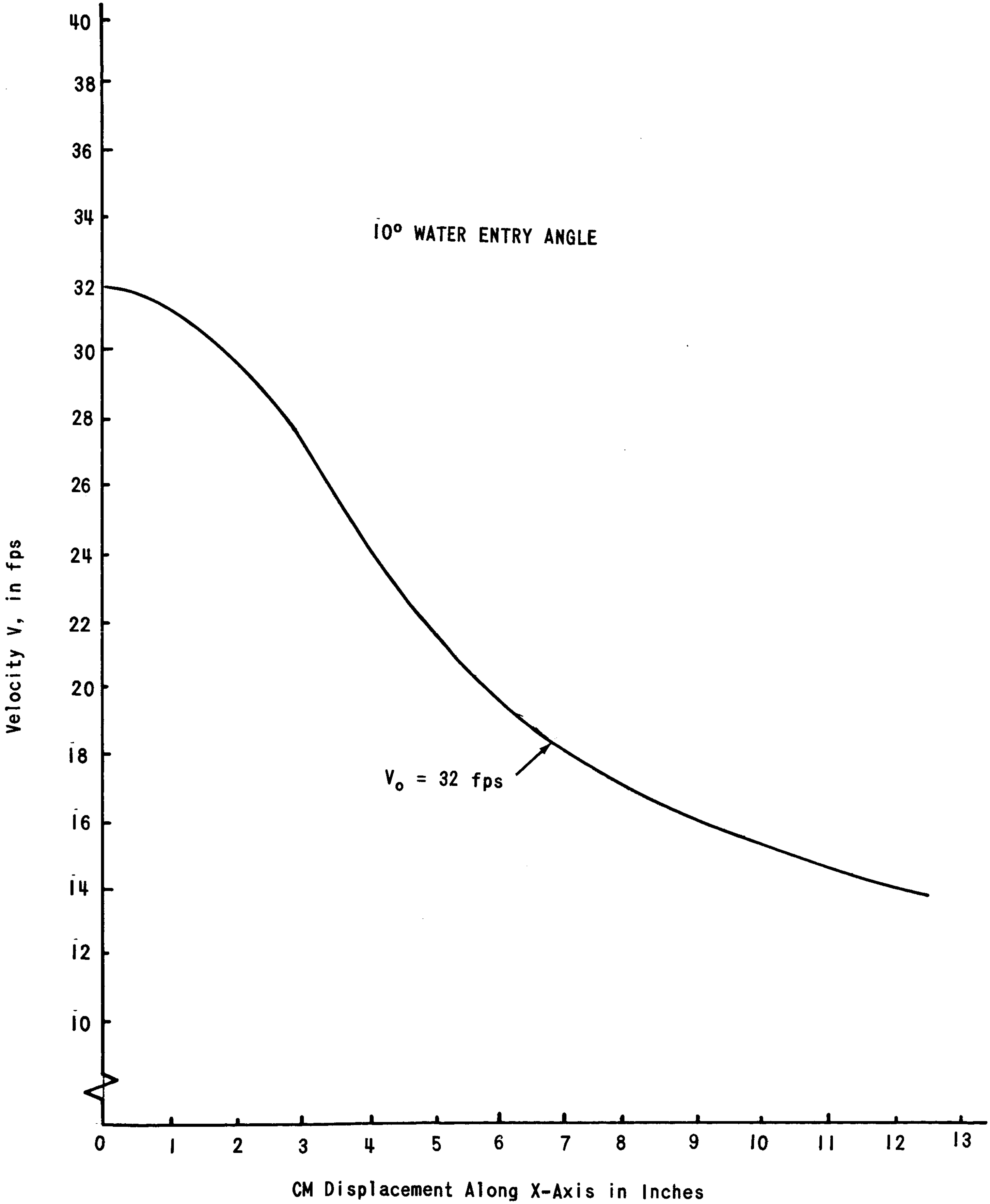
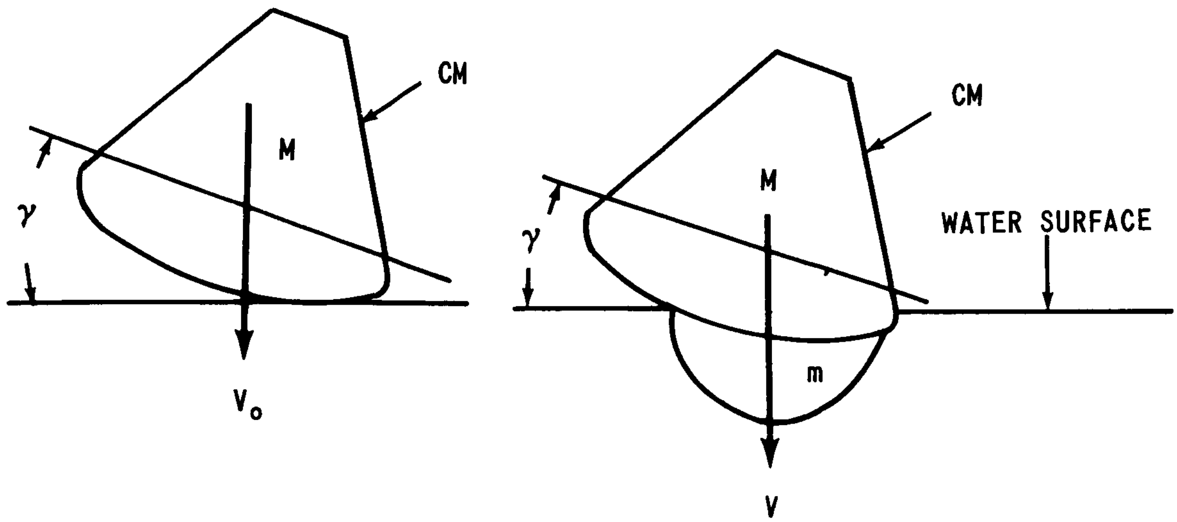


FIGURE 11 - CALCULATED CM DISPLACEMENT AND VELOCITY ALONG THE X-AXIS DURING THE IMPACT PHASE OF WATER LANDING



$MV_o = (M + m)V$

M = MASS OF CM

m = VIRTUAL MASS OF WATER ATTACHED TO CM

V_o = VERTICAL VELOCITY OF CM BEFORE IMPACT

V = VERTICAL VELOCITY OF CM AFTER IMPACT

γ = WATER ENTRY ANGLE = CONSTANT

FIGURE 12 - VON KARMAN IMPACT THEORY

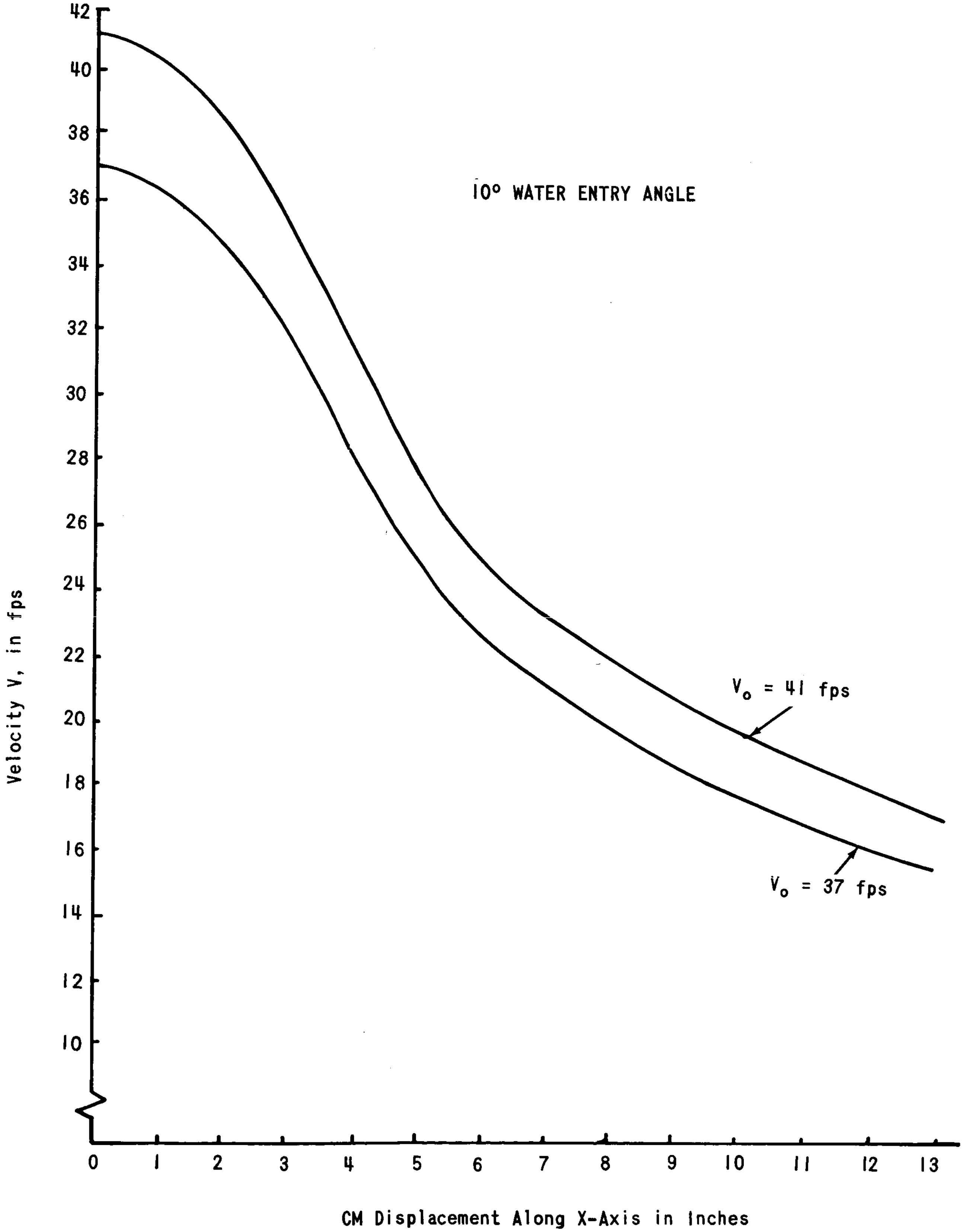


FIGURE 13 - CALCULATED CM DISPLACEMENT AND VELOCITY ALONG THE X-AXIS DURING THE IMPACT PHASE OF WATER LANDING

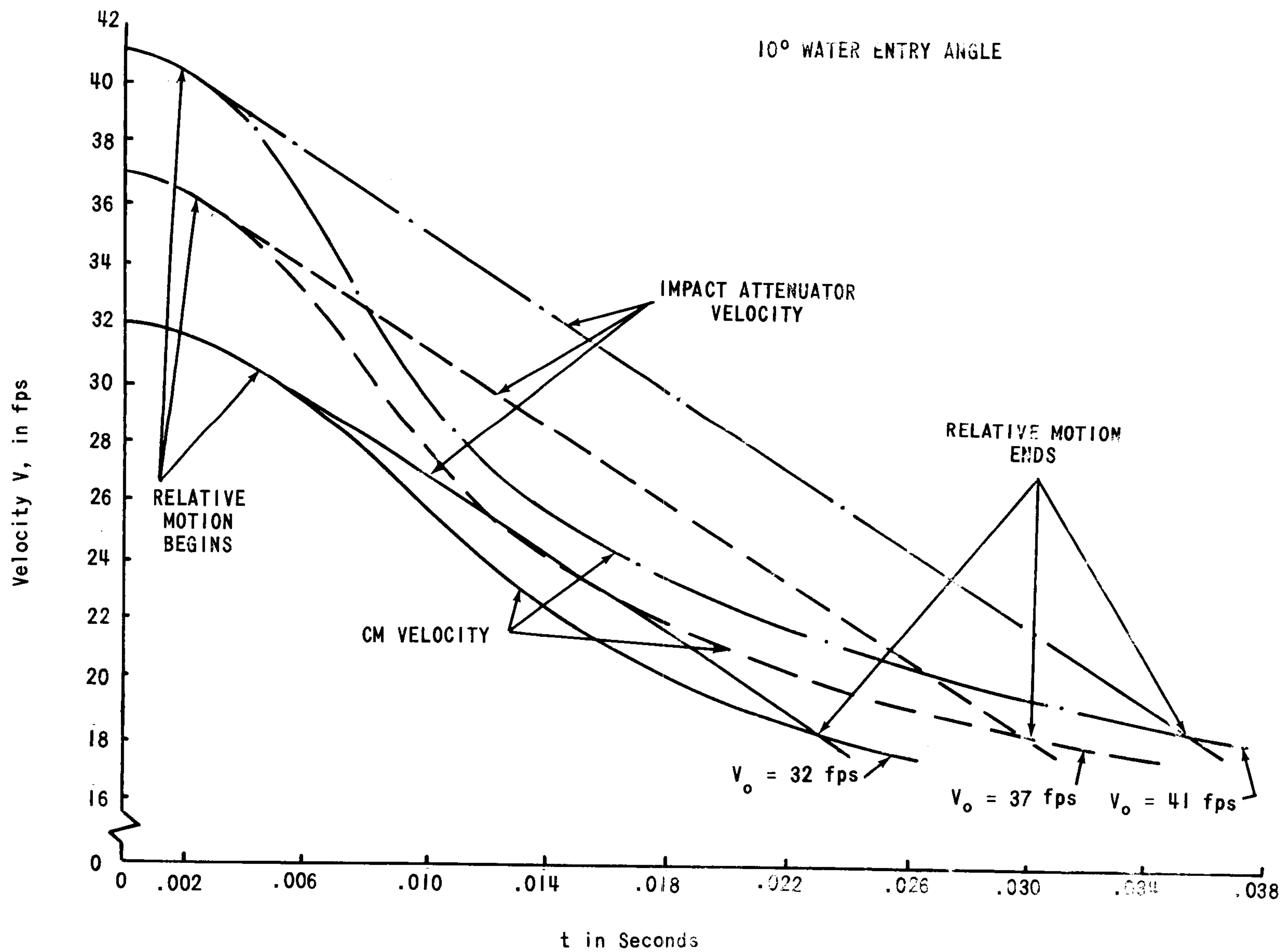


FIGURE 14 - MOTION OF CM AND IMPACT ATTENUATOR

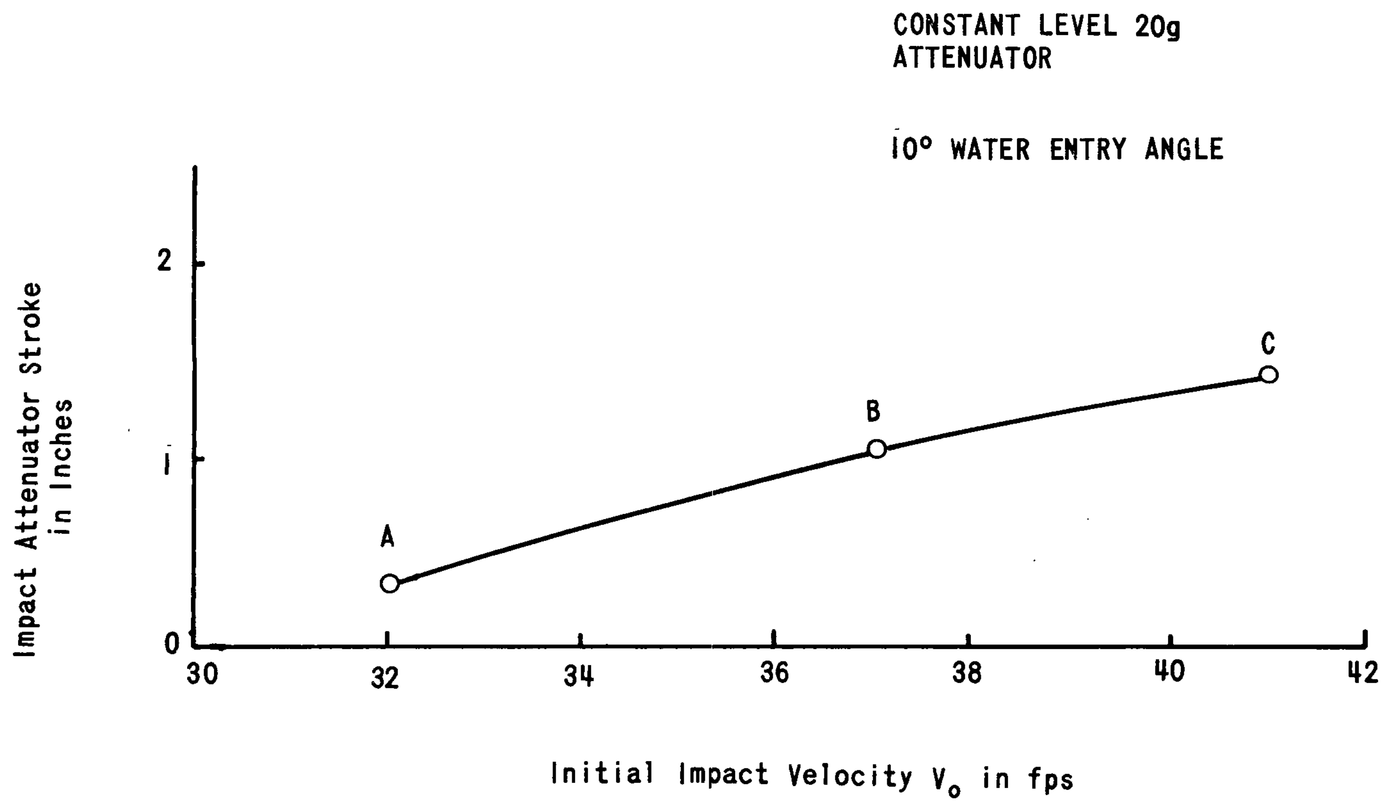


FIGURE 15 - CALCULATED CREW COUCH X-AXIS IMPACT ATTENUATOR STROKE

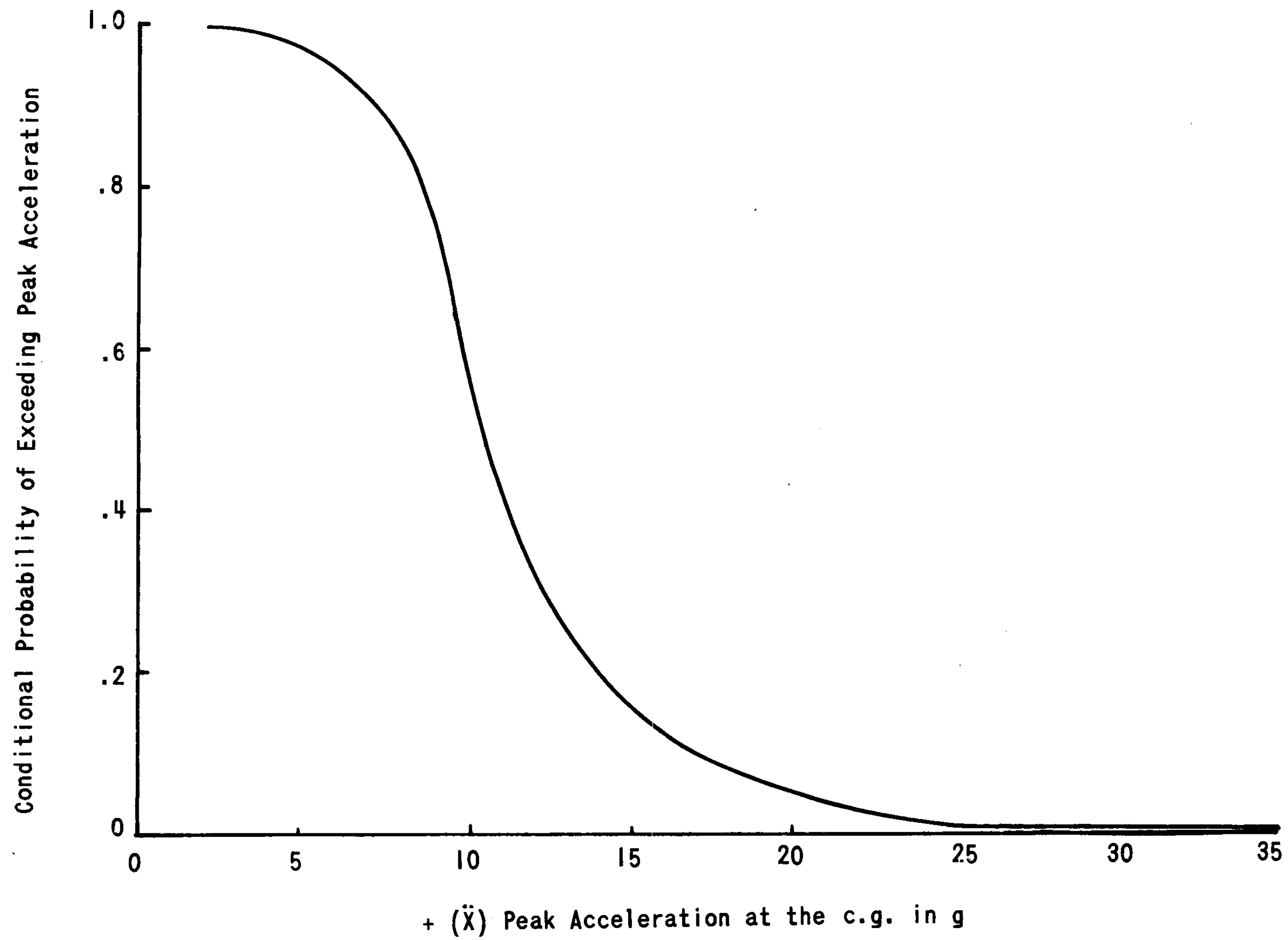


FIGURE 16 - CM PEAK ACCELERATION CONDITIONAL PROBABILITIES (THREE MAIN PARACHUTES)

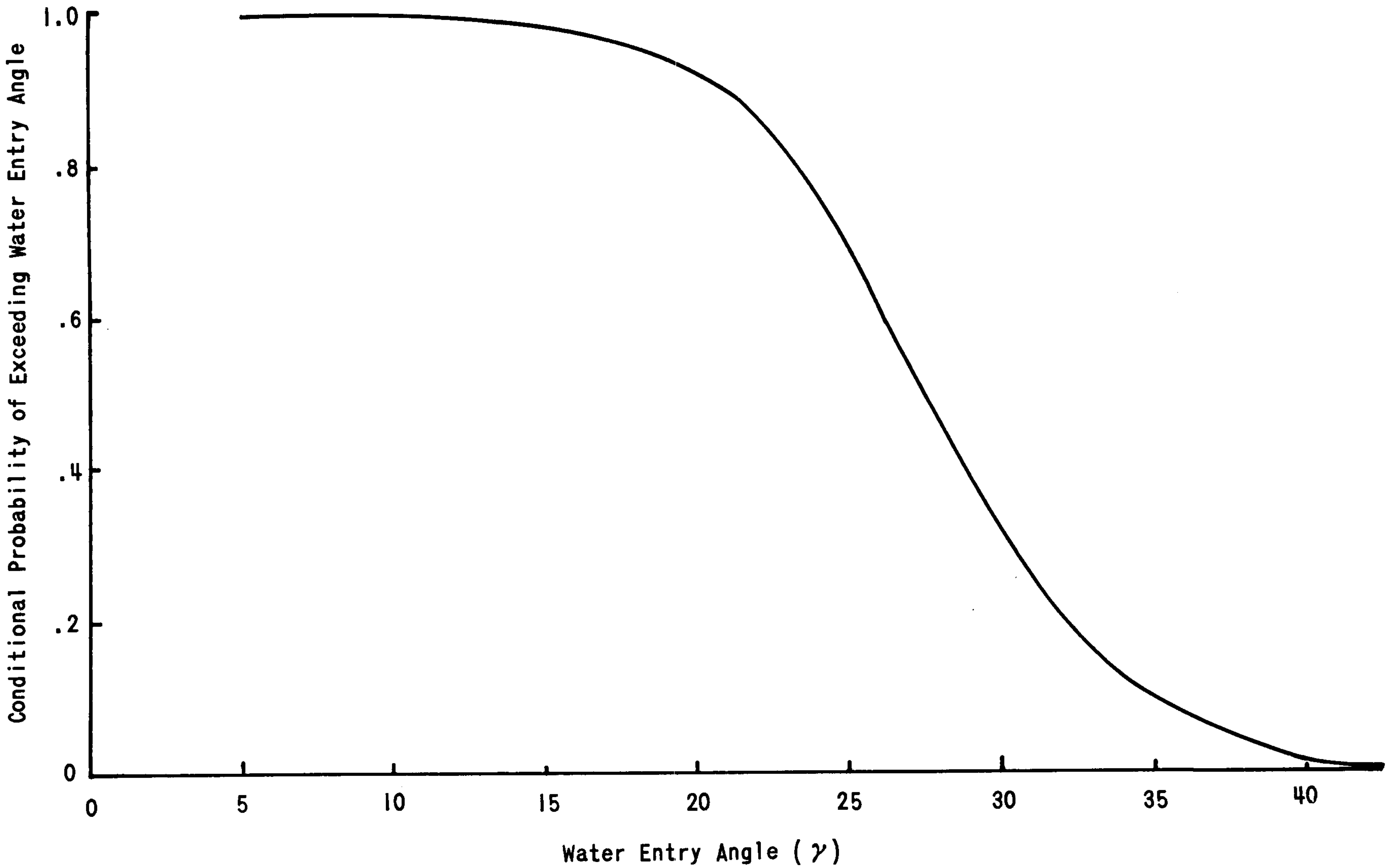


FIGURE 17 - WATER ENTRY ANGLE CONDITIONAL PROBABILITIES (THREE MAIN PARACHUTES)

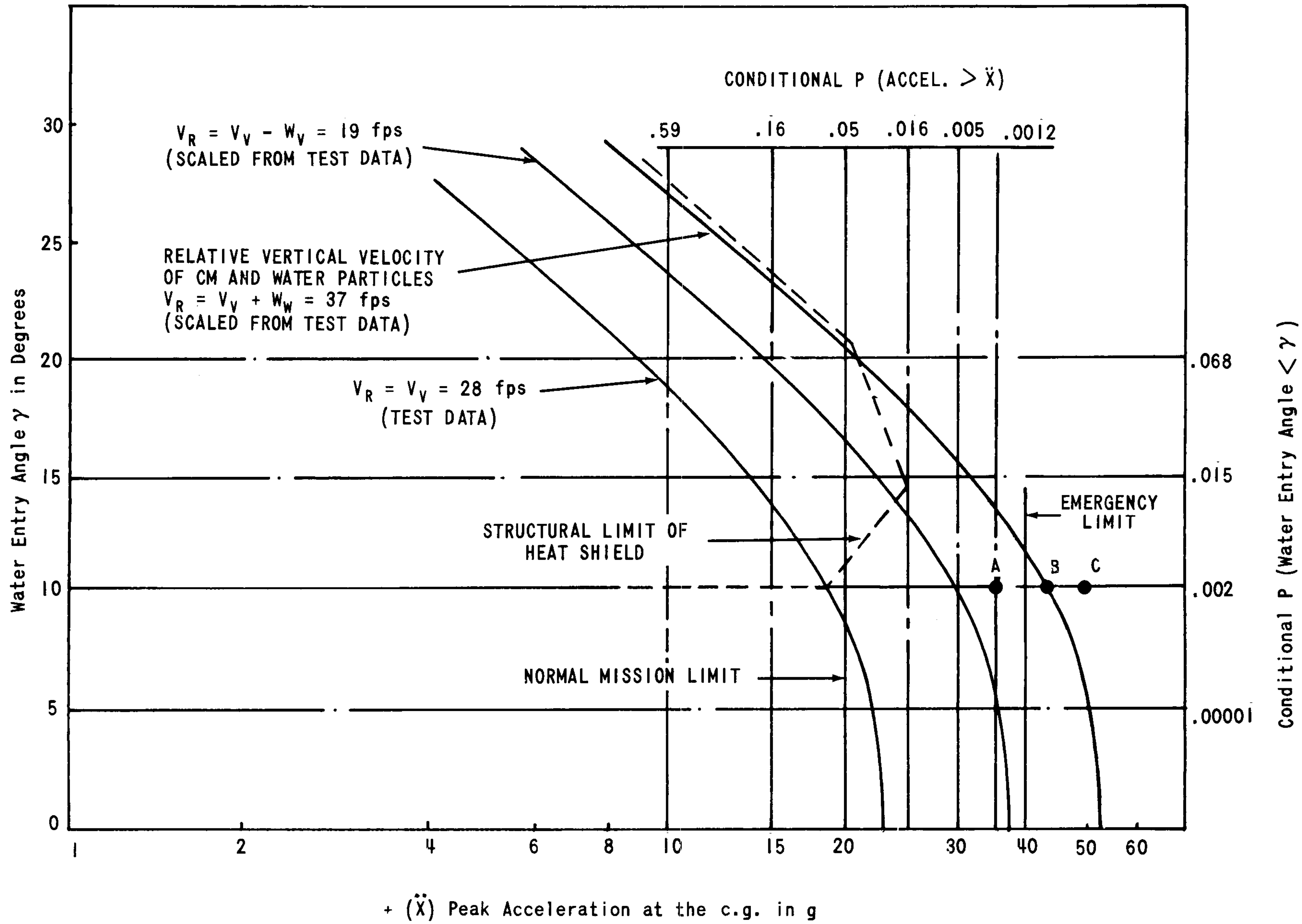


FIGURE 18 - CM WATER LANDING PEAK IMPACT ACCELERATIONS AND CONDITIONAL PROBABILITIES (THREE MAIN PARACHUTES)